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(54) [Title of the Invention] FIELD EMISSION DEVICE AND MANUFACTURING METHOD THEREOF

(57) [Abstract]

[Object] A method for making a field emission device having corrugated support pillars that improve the resistance to breakdown, in particular, a method for making a novel support pillar that can be used in high voltage operation without inflicting breakdown or arcing are provided.

[Solving Means] A field emission device is made by providing electrodes to the device, forming a plurality of corrugated insulating rods with discontinuous coatings of a conductive or semiconductor material with low secondary electron emission coefficient, attaching the rods to an

electrode, cutting the rods to define corrugated pillars, and finishing the device.

[Claims]

[Claim 1] An electron field emission device (90) comprising an electron emitter cathode (92), an anode (93), and a plurality of insulating pillars (96) separating the electron emitter cathode (92) and anode (93),

wherein at least one of the pillars (96) comprises a corrugated rod of an insulating material, the corrugations comprising ridges and recessed regions, the ridges of the corrugations being selectively coated with a conductive material.

[Claim 2] A method for making an electron field emission device comprising an electron emitter cathode electrode (92), an anode electrode (93), and a plurality of insulating pillars (96) separating the electrodes, comprising the steps of:

preparing the electrodes;

forming a corrugated rod of an insulating material, the corrugations being provided with ridges;

selectively applying a conductive material to the ridges of the corrugations;

attaching the rod to one of the electrodes;

cutting the rod; and

finishing the electron field emission device.

[Detailed Description of the Invention]

[0001]

[Technical Field of the Invention] The present invention relates to methods for making improved field emission devices and, in particular, to a method for making a field emission device, such as a flat panel display, having corrugated and locally conductive support pillars for improving resistance to breakdown.

[0002]

[Description of the Related Arts] Field emission of electrons into vacuum from suitable cathode materials is useful for a variety of field emission devices including flat panel displays. Support pillars are important components of field emission devices (hereinafter also referred to as "FEDs"), such as flat panel displays. A typical field emission device includes a cathode that has a plurality of field emitter tips, and an anode spaced from the cathode. A voltage applied between the anode and cathode induces emission of electrons towards the anode. In flat panel displays, an additional electrode called a gate is typically disposed between the anode and cathode to selectively activate desired pixels. The space between the cathode and anode is evacuated, and integrated cylindrical support pillars keep the cathode and anode separated. Without support pillars, the atmospheric pressure outside would bring the surfaces of the anode and cathode into contact with each other. Pillars are typically 100 to 1,000

μm high and each provides support for an area of 1 to 10,000 pixels.

[0003] Cylindrical pillars can provide sufficient mechanical support but are not best suited for new field emission devices that employ higher voltages. The present inventors have found that increasing the operating voltage between the emitter cathode and the anode can substantially increase the efficiency and extend the operating life of a field emission device. For example, in a flat panel display, changing the operating voltage from 500 V to 5,000 V could centuple the operating life of a typical phosphor. However, breakdown and arcing that occur along the surfaces of the cylindrical pillars preclude the use of such high voltages.

[0004] If cylindrical insulators are disposed between two electrodes and a continuous voltage gradient is applied to the cylindrical insulators, then emitted electrons colliding with the insulators can stimulate the emission of secondary electrons. These secondary electrons are accelerated toward the positive electrode and cause runaway. As a result, the insulators become positively charged and an arc forms along the surface of the insulator. A new pillar design that will permit the use of higher voltages without breakdown or arcing is desired.

[0005] Co-pending US applications "Method For Making Field Emission Devices Having Corrugated Support Pillars for

Breakdown Resistance" and "Multilayer Pillar Structure For Improved Field Emission Devices" filed concurrently herewith disclose a corrugated insulator pillar structure and a multilayer pillar structure, and methods for producing such pillars. These novel structures increase the surface length of the insulator material and reduce the detrimental effect of secondary electron emission from the pillar surface.

[0006]

[Problems to be Solved by the Invention] The object of the present invention is to provide an improved support pillar structure that includes discontinuous conductive coatings, the structure achieving improved resistance to breakdown and arcing.

[0007]

[Means for Solving the Problems] According to the present invention, a field emission device is made by providing electrodes to the device; forming a plurality of corrugated insulating rods with discontinuous coatings of a conductive or semiconductor material with low secondary electron emission coefficient; cutting the rods to form corrugated support pillars; and finishing the device.

[0008]

[Embodiments] There are five considerations in optimal pillar design. First, the optimal pillar design is one where surface paths from negative to positive electrodes are

as long as possible for a given pillar height. Second, it is desirable to construct the pillar so that most secondary electrons will re-impact the pillar surface close to the point of their generation, rather than being accelerated a substantial distance toward the positive electrode. This goal is advantageous because most materials generate less than one secondary electron for each incident electron if the incident energy is less than 500 V (or preferably, less than 200 V). Under these conditions, secondary electrons will generally not have enough energy to make an increasing number of secondaries of their own. In order to achieve this goal, "close point" is defined as a point where the electrostatic potential is less than 500 V more positive than the point at which the electron is generated, and preferably less than 200 V more positive. Third, it is desirable to construct the pillar out of materials that have secondary electron emission coefficients of less than two, under the normal operating conditions. Fourth, it is desirable to have as much of the surface of the pillar oriented so that the local electric field is nearly normal to the insulator surface, preferably with the field lines emerging from the surface, so that secondary electrons will be pulled back toward the surface and re-impact with energies less than the above-mentioned 200 V or 500 V. Fifth, the pillar must not be so much wider at the anode end

so that it substantially reduces the area that can be allocated to the phosphor screen.

[0009] Where the field emission device is a flat panel display, the pillar material should be mechanically strong and also should be an electrical insulator with a high breakdown voltage in order to withstand the high electrical field applied to operate the phosphor of the flat panel display. For the established phosphor, such as Zn:SCu, Al, the breakdown voltage should be greater than 2,000 V, and preferably greater than 4,000 V.

[0010] The present invention will now be described with reference to the drawings. Fig. 1 is a flowchart showing steps in making an improved pillar structure for field emission devices. The first step (block A) is to provide a wire, rod, or plate of corrugated insulating material. The U.S. application "Method for Making Field Emission Devices Having Corrugated Support Pillars for Breakdown Resistance", which is co-pending with the U.S. application of the present invention, describes various methods for making such a corrugated geometry from insulating materials, such as glass, quartz, ceramic materials (oxides, nitrides), polymers, and composite materials.

[0011] The next step (block B in Fig. 1) is to deposit on the ridges of the corrugations a discontinuous film of conductor or semiconductor material with low secondary

electron emission coefficient, δ_{max}. The coefficient is defined as the ratio of the number of outgoing electrons to the number of incoming electrons on a given area of the material. Insulators typically have high δ_{max} of 2 to 20, e.g., 2.9 for glass and 20 or less for MgO. Conductors or semiconductors typically have low δ_{max} of less than 2. For FED pillar applications, a δ_{max} value close to 1 is desirable. δ_{max} much higher than 1 means undesirable electron multiplication. According to the present invention, examples of suitable materials for use as a discontinuous coating on the pillar include metals and semiconductors, such as Cu (δ_{max} = 1.3), Co (δ_{max} = 1.2), Ni (δ_{max} = 1.3), Ti (δ_{max} = 0.9), Au (δ_{max} = 1.4), and Si (δ_{max} = 1.1), and compounds, such as Cu_2O (δ_{max} = 1.23) and Ag_2O (δ_{max} = 1.0).

[0012] The combination of discontinuous conductor coating on the protruding ridges of the corrugated insulating pillar and recessed grooves is particularly useful in improving the resistance to high voltage breakdown because it provides increased surface length, secondary electron trapping inside the grooves, and minimum electron multiplication on the exposed, protruding surface portion (ridges or peaks) of the corrugated pillar.

[0013] Figs. 2A and 2B schematically illustrate a first method of selectively adding an electrode 21 to a corrugated rod 20 by inclined angle deposition (e.g., evaporation,

sputtering, or spray coating technique). Because of the line-of-sight deposition of the film material, the deposition is naturally limited to the ridge or peak portion of the corrugated rod or corrugated plate. The deposition can be carried out in a continuous manner if a long wire or plate-shaped corrugated material is slowly moved away during deposition. A rotation of the rod can be utilized to ensure uniform deposition on all sides of the wire surface (Fig. 2A).

[0014] A low δ_{max} metal or compound can be directly deposited. Alternatively, a precursor containing the desired δ_{max} material may be deposited first and decomposed or pyrolized during the later stage of processing. For example, NiO or $Ni(OH)_2$ may be deposited for Ni coating, and CuO (evaporated) or $CuSO_4$ (spray coated as an aqueous solution, optionally with a binder added for enhanced adhesion, e.g., polyvinyl alcohol) may be deposited for Cu or Cu_2O coating.

[0015] A second method of depositing the discontinuous film of low δ_{max} material is schematically illustrated in Fig. 3. In the method shown in Fig. 3, a wire 30 of corrugated insulating material is continuously wiped off with a wiping cloth 31 or sponge-like material lightly wetted with a suspension or slurry containing fine particles (with a size of 20 μm or less, preferably 2 μm or less) of low δ_{max}

material (e.g., Cu, Co, Cu_2O, or Ag_2O) or a precursor liquid (e.g., $CuSO_4$ or $NiCl_2$ solution). To the ridges or protruding portions of the insulating wire is applied a coating 32 of the fine particles, slurry or precursor, and the slurry or precursor is later decomposed, sintered, or melted by heat treatment to leave only the desired low δ_{max} material.

[0016] Alternatively, the application of the coating 32 may be carried out with a catalyst for ease of subsequent electroless or electrolytic deposition. For example, the wiping cloth 31 in Fig. 3 may be wetted with a palladium-containing solution to be applied to the protruding wire surface. Palladium is a known catalyst which promotes adherence of metal to a substrate during electrochemical deposition. After optional baking process for prompt decomposition of the solution, electroless or electrolytic plating (e.g., with Cu, or Sn) is carried out for selective metal deposition on catalyst-applied, protruding portions of the grooved insulating pillar wire.

[0017] A third method of discontinuously depositing low δ_{max} coating is schematically illustrated in Fig. 4. In the method of Fig. 4, one of the methods for shaping the corrugated structure disclosed in the U.S. application "Method for Making Field Emission Devices Having Corrugated Support Pillars for Breakdown Resistance", which is co-pending with the U.S. application of the present invention,

is employed, in which an inert metal mask, such as an Au film, is used to etch out grooves in glass fiber or quartz fiber using hydrofluoric acid. The mask used in the etching process may be left on, which is then used as a base for electroplating of a lower δ_{max} material (e.g., Co) if desired. The masked, grooved insulating wire 41 is placed in a bath of electrolyte 44 between a cathode 43 and an anode 45. During the electroplating process of Fig. 4, the Au metal mask 40 on the insulating wire 41 is kept in contact with the plating electrode (cathode) 43 by gentle pressing with a flexible material, such as fine metal gauge or conductive elastomer. The wire is advantageously rotated slowly for uniform coating.

[0018] The desired thickness of the discontinuous coating of low δ_{max} material applied by the process of Fig. 1 is typically in the range of 0.005 to 50 μm, and preferably in the range of 0.1 to 2.0 μm. Microscopically rough coating is preferred because microscopic geometrical trapping in the coating itself reduces the number of secondary electrons from the coating surface.

[0019] The next step in Fig. 1 (block C) is to heat-treat the deposited film to improve the adhesion, to melt and densify the low δ_{max} material, or to decompose the precursor coating. Typically, a hydrogen-containing atmosphere is used for the heat treatment to obtain pure metal films or

alloy films. An inert gas atmosphere, oxygen-containing atmosphere, or nitrogen-containing atmosphere can be used for heat treatment of oxide, nitride, or other compound films. Although the heat-treating temperature and time vary depending on the nature of metals or precursors, the heat treatment is performed typically in the range of 100° C to 900° C for 0.1 to 100 hours.

[0020] The final step in Fig. 1 (block D) is to cut the wire into desired pillar length and assembled into a field emission display device between the cathode and the anode.

[0021] Instead of processing on a corrugated wire as described above, a non-corrugated wire may be used as a starting material for processing as illustrated in Fig. 5. The first step shown in block A of Fig. 5 is to provide a non-corrugated insulating rod or wire, such as the one shown in Fig. 6A as a rod 60.

[0022] The next step in Fig. 5, block B, is to deposit a continuous layer of low secondary electron emission conductor or precursor. In Fig. 6B, this continuous layer is denoted by reference numeral 61.

[0023] The third step (Fig. 5, block C) is to mask the rod 60 coated with a metal mask material shown in Fig. 6C as masking elements 63.

[0024] The next step in block D of Fig. 5 is to form grooves by selectively etching the insulating material of

the rod 60. The resulting structure has grooves 64 as shown in Fig. 6D.

[0025] The metal mask material that resists etching in hydrofluoric acid processing for groove etch-out is chosen in such a way that the metal also has low δ_{max} characteristics. In such a case, the mask material can be simply kept and used as a low δ_{max} coating on the exposed ridges, without having to add another low δ_{max} metal, thus reducing the production cost. Such a low δ_{max} metal that resists etching by hydrofluoric acid can be Au itself (δ_{max} = 1.4). The similar low δ_{max} mask can be accomplished by alloying Au or Pt, for example, with a lower δ_{max} metal, such as Co, Cu, or Al. The desired alloy composition is 40 to 80 atomic percent Au, with the remainder made up of the selected alloying elements. Binary alloys, ternary alloys, or higher order alloys may also be used. The desired alloy is exemplarily first deposited on a round wire of insulating material as a continuous film, for example, by physical, chemical, or electrochemical means, or other known techniques, (refer to Fig. 6B), patterned, for example, by photolithography or mechanical means, into a zebra-shape or other vertically discontinuous configuration (refer to Fig. 6C), and then etched by hydrofluoric acid treatment as shown in Fig. 6D. Alternatively, the zebra-shaped metal layer can be directly obtained by deposition through a patterned mask.

[0026] A typical geometry of the pillar is advantageously a modified form of a round or rectangular rod. The diameter or thickness of the pillar is typically 50 to 1,000 μm, and preferably 100 to 300 μm. The height-to-diameter or height-to-thickness aspect ratio of the pillar is typically in the range of 1 to 10, preferably in the range of 3 to 6. The desired number or density of the pillars depends on various factors to be considered. For sufficient mechanical support of the anode plate, a larger number of pillars is desirable. However, in order to reduce the production cost and to minimize the loss of display pixels for the placement of pillars, some compromise is necessary. A typical density of the pillar is about 0.01% to 2%, and preferably 0.05% to 0.5%, of the total display surface area. A FED display of about 25×25 cm^2 area having approximately 500 to 100,000 pillars, each with a cross-sectional area of 100×100 μm^2, is a good example.

[0027] After the corrugated rods are formed and the low δ_{max} coating is added, the next step is to attach the ends of a plurality of rods to an electrode of the field emission device, preferably the electron emitting cathode. The placement of pillars on the electrode can conveniently be accomplished by using the apparatus illustrated in Fig. 7. Specifically, a plurality of corrugated rods 20 are applied to an electrode 21 through apertures 26 in a two-part

template comprising an upper portion 23 and a lower portion 24. In the insertion phase, the apertures 25 of the upper template and the apertures 26 of the lower template are aligned with each other and with positions on the electrode where the pillars are to be attached. Adhesive spots 27 on the projecting ends of the corrugated rods 20 may be provided to unite the corrugated rods 20 with the electrode 21. In the example shown in the drawing, the electrode 21 is the device cathode emitter region including wires 30 on a conductive substrate 22. Each coating 32 is separated from the conductive substrate 22 by an insulating layer 33.

[0028] For example, in a FED display requiring 1,600 pillars, display-sized templates (e.g., a metal sheet with drilled holes at the desired pillar locations), are first prepared. Long wires of corrugated insulating material are simultaneously and continuously supplied through one to all of the holes (or typically, 49 pillars in one row). The protruding bottoms of the wires are applied with an adhesive (such as uncured or semicured epoxy), low melting point glass, solder that is molten or in the paste form, or an optical absorbing layer.

[0029] The corrugated rods need to be cut into support pillars. This can be advantageously done by shearing with the apparatus of Fig. 7. The upper template 23 is moved sideways while the lower template 24 is fixed with the

adhesive in contact with the display cathode surface, so that bottom pillar is broken away at the pre-designed V-notch location 28. This process is repeated for the next display substrate. Since many of the pillars are placed simultaneously, the assembly can be fast and of low cost. If desired, local heating may be supplied by a focused light beam, e.g., a laser, to cure epoxy or to fuse the pillars to the conductive substrate 22.

[0030] The device assembly is completed by applying the other electrode and evacuating and sealing the space between the two electrodes. Typically, in the assembly, glass sealing and evacuation process is substantially required when the device is heated (e.g., 300° C to 600° C). This heat-treating step may substitute for step C in Fig. 1. Similarly, a heating step during device assembly may be advantageous in the process of Fig. 5. For example, due to the etching step (step D in Fig. 5) of an alloy film (e.g., Au-Cu alloy), Cu tends to be depleted from the surface. The heating step will allow the low δ_{max} component (Cu in this case) to diffuse to the surface so as to reduce the secondary electron emission.

[0031] The preferred use of these corrugated rods is in the fabrication of field emission devices, such as electron emission flat panel displays. Fig. 8 is a schematic cross section of an exemplary flat panel display 90 using the high

breakdown voltage pillars according to the present invention. The display comprises a cathode 91 including a plurality of electron emitter regions 92 and an anode conductor layer 93 disposed in spaced relation from the electron emitter regions 92 within a vacuum seal. The anode conductor 93 formed on a transparent insulating substrate 94 is provided with a phosphor layer 95 and is mounted on support pillars 96. A perforated conductive gate electrode 97 is placed between the cathode 91 and the anode conductor layer 93 and closely spaced from the electron emitter regions 92.

[0032] The space between the anode conductor layer 93 and the electron emitter regions 92 are sealed and evacuated, to which a voltage is applied by a power supply 98. The field-emitted electrons from the electron emitter regions 92 are accelerated by the gate electrode 97 from multiple electron emitter regions 92 on each pixel and move toward the anode conductive layer 93 (typically transparent conductor, such as indium tin oxide) coated on the transparent insulating substrate 94. The phosphor layer 95 is disposed between the electron emitter regions 92 and the anode conductor layer 93. When the accelerated electrons hit the phosphor, a display image is generated.

[0033] It is to be understood that the embodiments described above are illustrative of only a few of the many possible specific embodiments which can represent

applications of the principles of the present invention. For example, the high breakdown voltage pillars of the present invention can be used not only for flat panel displays but also for other applications, such as x-y matrix addressable electron sources for electron beam lithography or for microwave power amplifier tubes.

[0034]

[Advantages] As is previously described, the present invention provides a novel support pillar that can operate at high voltages without causing breakdown or arcing. Furthermore, according to the present invention, a field emission device having superior resistance in high-voltage operation can be manufactured at low costs.

[0035] The reference numerals in the claims are inserted to facilitate understanding of the invention and do not limit the scope of the claims.

[0036] According to the above-described means for solving the problem, a field emission device having a superior resistance in high-field operation can be manufactured at low costs.

[Brief Description of the Drawings]

[Fig. 1] Fig. 1 is a schematic block diagram of steps for making an improved support pillar structure of a field emission device according to the present invention.

[Fig. 2] Fig. 2 shows a first method for forming conductor

coating on a corrugated rod used in the process of Fig. 1.

[Fig. 3] Fig. 3 shows a second method for forming conductor coating on the corrugated rod used in the process shown in Fig. 1.

[Fig. 4] Fig. 4 shows a third method for forming conductive coatings on the corrugated rod used in the process of Fig. 1.

[Fig. 5] Fig. 5 is a schematic flow chart of steps for preparing a conductor-coated corrugated support pillar structure from an uncorrugated insulator rod.

[Fig. 6] Fig. 6 shows a method employed in the process shown in Fig. 5.

[Fig. 7] Fig. 7 is a diagram showing an example method for placing the support pillars on a FED device.

[Fig. 8] Fig. 8 is a schematic diagram of an example FED device including the conductor-coated corrugated pillars.

[Reference Numerals]

20: corrugated rod

21: electrode

22: conductive substrate

23: upper template

24: lower template

25: aperture

26: aperture

27: adhesive spot

28: V-notch

30: wire

31: wiping cloth

32: coating

33: insulating layer

40: Au metal mask

41: insulator wire

43: cathode

44: electrolyte bath

45: anode

60: rod

61: continuous layer

63: masking element

64: groove

90: flat panel display

91: cathode

92: electron emitter region

93: anode conductor layer

94: transparent insulator substrate

95: phosphor layer

96: support pillar

97: gate electrode

98: power supply

FIG. 1

A: PREPARE A WIRE, WHICH IS A CORRUGATED INSULATOR MATERIAL

B: DEPOSIT A CONDUCTIVE MATERIAL FILM HAVING A LOW SECONDARY ELECTRON EMISSION COEFFICIENT ON RIDGES OF THE PILLAR

C: HEAT THE DEPOSITED FILM TO IMPROVE ADHESION OR TO DECOMPOSE THE PRECURSOR MATERIAL FILM

D: CUT TO THE LENGTH OF THE WIRE SUPPORT PILLAR AND ASSEMBLE INTO FIELD EMISSION DISPLAY DEVICE

FIG. 2

20: INSULATOR

21: MATERIAL WITH LOW SECONDARY ELECTRON EMISSION COEFFICIENT

FIG. 3

30: WIRE

31: WIPING CLOTH

32: COATING

FIG. 4

40: Au METAL MASK

41: INSULATOR WIRE

43: CATHODE

44: ELECTROLYTE BATH

45: ANODE

FIG. 5

A: PREPARE NON-CORRUGATED INSULATOR PILLAR WIRE

B: DEPOSIT CONTINUOUS LAYER OF PRECURSOR MATERIAL, i.e., LOW-SECONDARY-ELECTRON-EMISSION CONDUCTOR

C: FORM STRIPED MASK ON THE COATED AREA

D: SELECTIVELY ETCH OUT BASE INSULATING MATERIAL TO FORM RECESSES

E: CUT TO THE LENGTH OF THE PILLAR AND ASSEMBLE INTO FIELD EMISSION DEVICE

FIG. 6

60: ROD

61: CONTINUOUS LAYER

63: MASKING ELEMENT

64: GROOVES

FIG. 7

10: ELECTRON EMITTER REGION

11: CONDUCTIVE GATE

12: INSULATING LAYER

20: CORRUGATED ROD

21: ELECTRODE

22: CONDUCTIVE SUBSTRATE

23: UPPER TEMPLATE

24: LOWER TEMPLATE

25: APERTURE

26: APERTURE

27: ADHESIVE SPOT

28: V-NOTCH

FIG. 8

50: CYLINDRICAL INSULATOR ROD

90: FLAT PANEL DISPLAY

91: CATHODE

92: ELECTRON EMITTER REGION

93: ANODE CONDUCTOR LAYER

94: TRANSPARENT INSULATOR SUBSTRATE

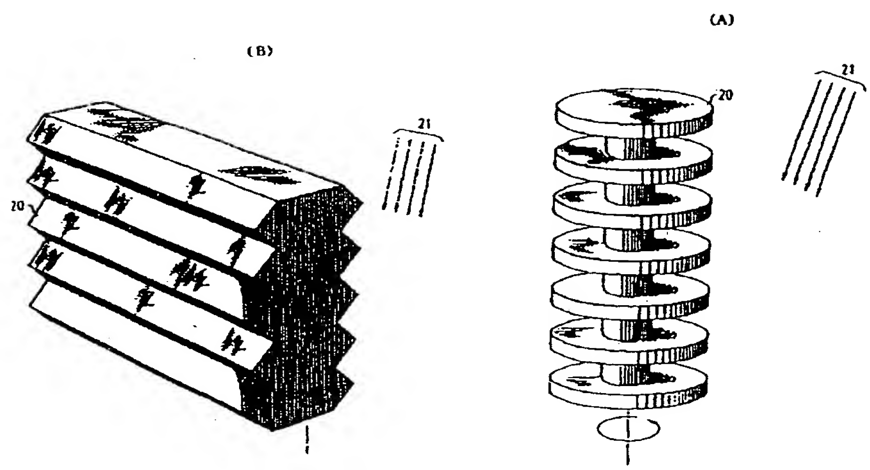
95: PHOSPHOR LAYER

96: SUPPORT PILLAR

97: GATE ELECTRODE

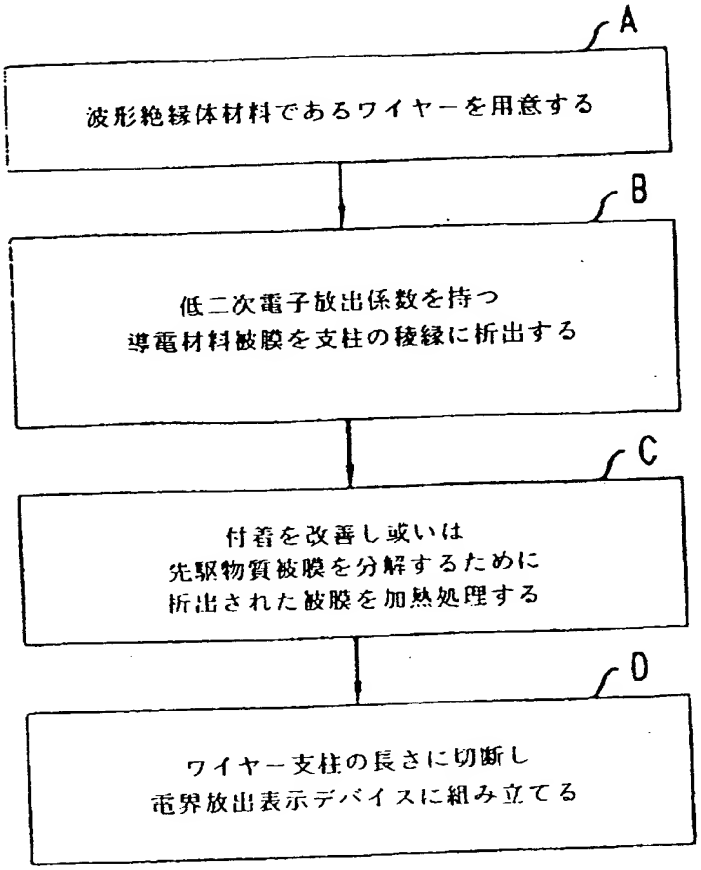
98: ELECTRODE

【図2】 FIG. 2

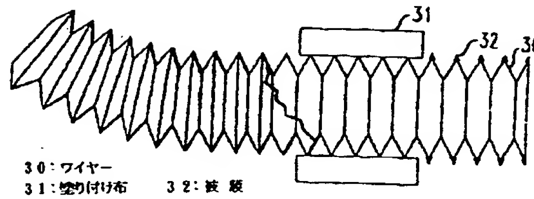


２０：絶縁体　　２１：低二次電子放出係数材料

【図1】 FIG.1

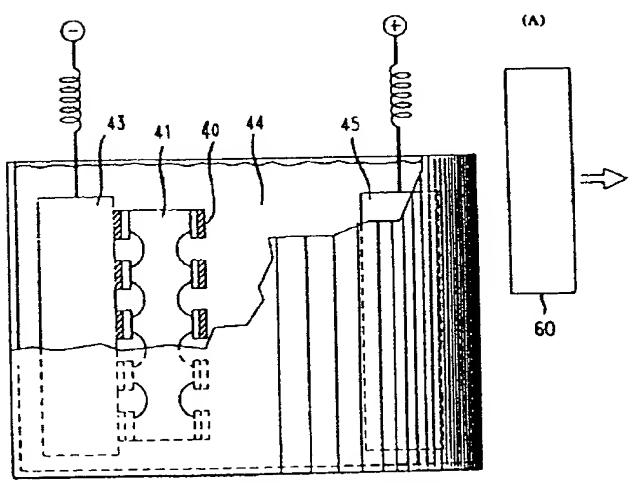


【図3】 FIG.3



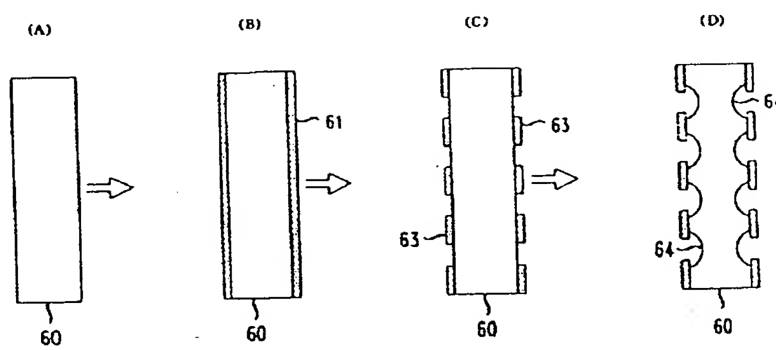
30：ワイヤー
31：塗り付け布　　32：被膜

【図4】 FIG.4



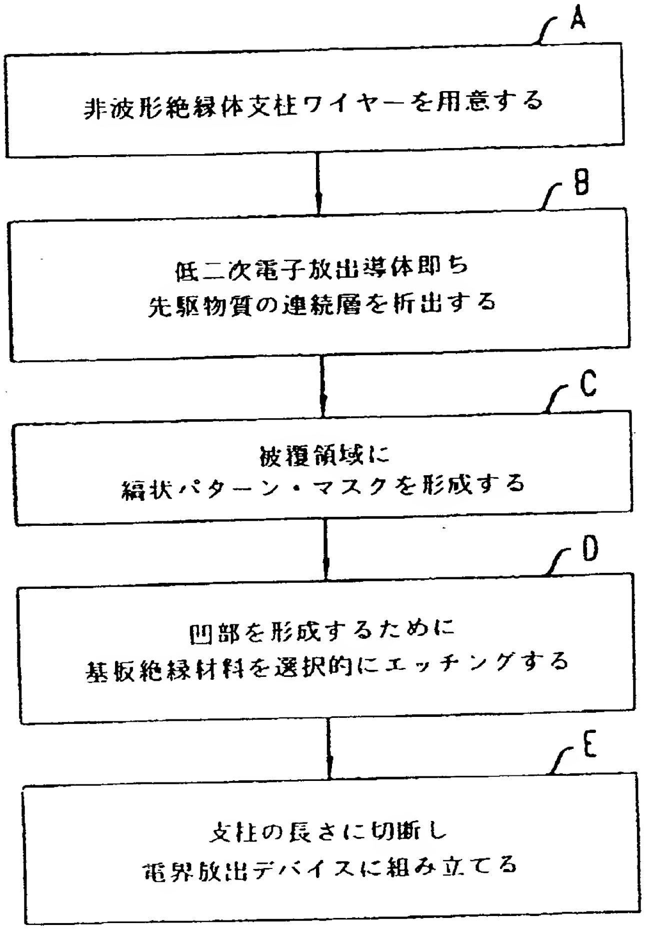
40：Auメタル・マスク　　41：絶縁体ワイヤー　　43：カソード
44：電解溶液　　45：アノード

【図6】 FIG.6

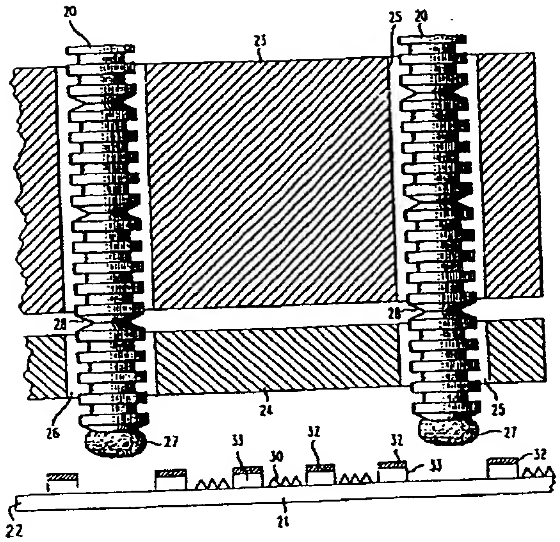


60：ロッド　　61：連続層　　63：マスキング部材　　64：溝

【図5】 FIG.5

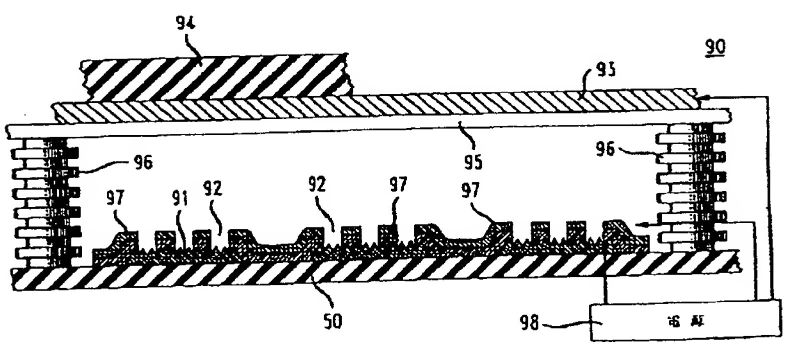


【図7】 FIG.7



10：電子放出体領域　11：導電性ゲート　12：絶縁層　20：波形ロッド
21：電極　22：導電性基板　23：上壁板　24：下壁板
25：孔　26：孔　27：接着剤スポット　28：V字形切り込み

【図8】 FIG.8



50：円筒形絶縁体ロッド　90：フラット・パネル・ディスプレイ　91：カソード
92：電子放出体領域　93：アノード導体層　94：透明絶縁体基板
95：蛍光体層　96：支柱　97：ゲート電極